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THE AERONAUTICAL RESEARCH INSTITUTE OF SWEDEN

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A MASS-FLOW PROBE FOR MEASUREMENT IN HIGH-ENTHALPY SUPERSONIC BOUNDARY LAYERS

BY

Gunnar Hovstadius

STOCKHOLM 1977

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(6) A MASS-FLOW PROBE FOR MEASUREMENT IN HIGH-ENTHALPY SUPERSONIC BOUNDARY LAYERS

by

(10) *Gunnar Hovstadius*

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SUMMARY

A system for mass-flow measurement in supersonic boundary layers has been examined. The mass flow is evaluated from measurements of pressure derivatives in a closed volume under controlled temperature conditions.

The advantages with respect to previous systems are, mainly, that fewer parameters are involved in the data reduction and that the pressure level in the system can be made arbitrarily low, thereby reducing the risk of detachment of the shock at the probe entrance. It is therefore possible to make measurements closer to the wall than has been possible earlier.

Measurements of boundary-layer properties have been made with the probe side by side with the AVA combined pressure-temperature probe in the FFA Hyp 500 wind tunnel.

The mass flows measured with the new system were compared with the mass flows calculated from measurements of stagnation temperature and stagnation pressure with the AVA probe. The results agree within the expected limit of accuracy.

Stockholm, March 1977

EINE MASSENSTROM-SONDE FÜR MESSUNGEN IN ÜBERSCHALL-GRENZSCHICHTEN HOHER ENTHALPIE

von

Gunnar Hovstadius

ZUSAMMENFASSUNG

Ein System zur Massenstrommessung in Ueberschallgrenzschichten ist untersucht worden. Der Massenstrom wird hergeleitet aus Messungen der Druckänderungen in einem geschlossenen Volumen bei konstant gehaltener Temperatur.

Die Vorzüge gegenüber existierenden Systemen sind: Man benötigt weniger Parameter in der Datenverarbeitung und das Druckniveau im System kann beliebig klein gemacht werden, und damit wird die Gefahr der Stossablösung am Eintritt zur Sonde geringer. Folglich lassen sich Messungen in grösserer Wandnähe ausführen als früher.

Die Messungen von Grenzschichtgrössen sind mit der Sonde, die neben der kombinierten Druck- und Temperatur-Sonde der AVA montiert war, im FFA HYP 500 Kanal ausgeführt worden.

Die Massenströme des neuen Systems sind verglichen worden mit denen, die sich aus Messungen der Ruheparameter und des Ruhedruckes der AVA-Sonde errechnen lassen. Die Ergebnisse stimmen in der erwarteten Genauigkeitsgrenze überein.

UNE SONDE DE L'ÉCOULEMENT DES MASSE POUR DES MÉSURES DANS DES COUCHES LIMITES SUPERSONIQUES DE HAUTE ENTHALPIE

par

Gunnar Hovstadius

RÉSUMÉ

Une méthode pour mesurer l'écoulement de masse dans des couches limites supersoniques a été examinée. L'écoulement de masse est évalué à partir des variations de pression dans un volume fermé avec température contrôlée.

Les avantages du système proposé en comparaison avec des méthodes existantes sont que pour la réduction des datas moins de paramètres sont utilisés et que le niveau de pression peut être arbitrairement bas, tenant le risque de séparation de choque à l'entré de la sonde plus petit. Il est alors possible de faire des mesures plus proche à la paroi qu'avant.

Des mesures des propriétés de la couche limite sont effectuées avec la sonde dans une position côté à côté avec la sonde combinée (pression et température) d'AVA dans la soufflerie FFA HYP 500.

L'écoulement de masse mesuré avec le nouveau système est comparé avec celui que est calculé à partir des mesures de température et pression de stagnation avec la sonde d'AVA. Les résultats sont en accord dans les limites de précision expectées.

CONTENTS

A MASS-FLOW PROBE FOR MEASUREMENT IN HIGH-ENTHALPY SUPERSONIC BOUNDARY LAYERS

by

Gunnar Hovstadius

1. INTRODUCTION

During the last few years, a system for mass-flow measurement in supersonic boundary layers has been developed and tested at FFA, Refs. [1] [2]. The work was initiated by R. Stalker, who designed the system shown in Fig. 1. This system uses a sharp-edged probe to capture the gas in a stream tube. The captured gas is taken through a heat exchanger to a plenum chamber, from which it escapes through a precalibrated orifice, operating at sonic conditions. Since the temperature in the plenum chamber is controlled by the heat exchanger, the outflow of gas mainly depends upon the pressure in the plenum chamber multiplied by the effective area of the sonic orifice. The system has proved to be reliable and simple to use. The main difficulty in the method is to determine the effective orifice area. The effective area of the orifice falls off with the pressure in the plenum chamber, and the lower the pressure the more uncertain is the calibration of the orifice. In order to obtain a reasonable degree of accuracy in the measurements it is therefore necessary to keep the pressure in the plenum chamber at a high level. This is in conflict with the need to have a low pressure in the system in order to ensure that the shock at the probe entrance remains attached. Results from mass-flow measurements with this probe have been compared with results from measurements with the AVA combined pressure-temperature probe, Ref. [3]. Those tests gave a better understanding of how the system worked but they also indicated that the method used has certain drawbacks.

The aim of the present work has been to modify the mass-flow system in order to remove these drawbacks. A different technique

for mass-flow measurement was used where the mass flow is calculated from the pressure rise in a volume connected to the probe. The pressure level in the system can be made arbitrarily low, which gives a larger margin to detachment of the probe-entrance shock, without affecting the accuracy of measurement. It is thus possible to obtain reliable measurements closer to the wall than before.

In order to check the measurements made with this modified system, the mass flow in the boundary layer has also been calculated from measurements of stagnation temperature and stagnation pressure with the AVA probe. The measurements were made with the probes side by side in the FFA Hyp 500 nozzle boundary layer at Mach number 4.

Similar systems have previously been used for mass-flow measurements in the free streams of low-density tunnels, Refs. [4], [5], [6]. However, the captured gas was at room temperature when entering the measuring volume and the pressure rise during the fill-up of the volume was slow enough for constant temperature to be assumed. If these probes were used at higher temperatures and densities, the measurements would probably be strongly influenced by temperature effects.

2. WIND TUNNEL

The experiments were carried out in the Hyp 500 wind tunnel at FFA. The tunnel is a blow-down-to-atmosphere wind tunnel with contoured axisymmetric nozzles and an open jet test section 50 cm in diameter, Ref. [7].

Summary of data

Mach number		4	7
Max stagnation pressure	MPa	2.4	12
Max stagnation temperature	K	800	800
Max flow rate	kg/s	100	35
Max running time	min	4	4
Nozzle exit	500 mm circular section		
Nozzle slenderness	length/exit diameter = 7		
Test section	free jet, test chamber volume 12 m^3		

The nozzles are made of hidumin RR58 and are water cooled through obliquely drilled conical channels which at the throat are 1.85 mm from the inner surface. The wall temperature does not exceed 220^{o}C. The working tolerance on the inner surface = 0.05 mm with a maximum angular error of 0.01^o on a measuring basis of 100 mm.

The Mach-number distribution in the M4 nozzle is shown in Fig. 2; Fig. 3 shows the probes mounted side by side in the nozzle.

3. TEST CONDITIONS

In the present tests the tunnel conditions were:

Mach number	4
Stagnation pressure	1.1 MPa
Stagnation temperature	475 K

The measuring position was located 1 cm downstream of the end of the nozzle such that the probes could be kept outside the nozzle during the starting up of the tunnel. The reason for this was that the thermocouple in the AVA-probe did not withstand the vibrations at the starting up of the tunnel when exposed to the flow.

4. TEST EQUIPMENT

4.1 Probes and traversing apparatus

Side-by-side measurements of boundary layer properties were made with the mass-flow probe and the AVA combined pressure-temperature probe. The probes were mounted on a traversing system that enabled the probes to traverse the boundary layer during a single run. The traversing apparatus could be manoeuvred from the outside to stop at an arbitrary position in the boundary layer for measurement of the mass flow, the pitot pressure, and the stagnation temperature.

The stagnation conditions of the wind tunnel, the position of the probes as well as p_v, T_1, T_2, T_3, T_4, and T_s were recorded.

A description of the mass-flow system and the AVA combined pressure-temperature probe is given below.

4.2 The mass-flow system

The mass-flow system is shown schematically in Fig. 4. For mass-flow measurements the valve to the vacuum system is first opened in order to lower the pressure in the system as much as possible. The mass flow into the probe is then calculated from the rate of change of the pressure in the system after closing the valve to the vacuum system. When the pressure is high enough in the system, the shock becomes detached at the probe entrance and finally the stagnation pressure is reached. Fig. 5 shows a typical pressure record.

The captured flow is cooled as soon as possible behind the probe intake by means of a heat exchanger. It is then led to a large volume which is filled with steel wool in order to absorb any heat of compression.

After the closure of the valve, the mass flow into the system is given by

$$\rho UA = \frac{d}{dt} \int_V \rho_V \, dv \tag{1}$$

where ρuA is the mass flow captured by the probe, ρ_V is the density in the measuring system, and V the volume of this system.

Using the gas law and changing the order of integration and derivation, the following expression is obtained

$$\rho uA = \int \frac{p_V}{RT_V} \left[\frac{\dot{p}_V}{p_V} - \frac{\dot{T}_V}{T_V} \right] dv \tag{2}$$

where the dots indicate derivation with respect to time.

The temperature [illegible] system is influenced by the hot gas entering the pr[illegible]nd by the production of heat when the gas is compressed. The first heat exchanger cools the hot flow entering the probe. The heat produced by the compression is absorbed by the steel wool. Thus the value of $\dot{T}_V/T_V$ can be made negligible compared with that of $\dot{p}_V/p_V$, and therefore

$$\rho uA = \int_V \frac{\dot{p}_V}{RT_V} \, dv \tag{3}$$

The volume V is now divided into subvolumes in which the respective temperatures can be considered as almost constant. $\dot{p}_V$ is assumed to be constant over the system. Thus

$$\rho uA = \sum_n \frac{\dot{p}_V \, V_n}{R \, T_{Vn}} = \frac{\dot{p}_V}{R} \cdot \sum_n \frac{V_n}{T_{Vn}} \tag{4}$$

In the data reduction the volume was divided into 4 subvolumes according to Fig. 6. In V_1 ($\approx$ 18 cm³) the temperature was

assumed to equal the local stagnation temperature, in V_2 ($\approx 25\ cm^3$) to the logarithmic mean temperature of the heat exchanger, and in V_3 ($\approx 30\ cm^3$) and in V_4 ($\approx 500\ cm^3$) to the measured temperatures T_3 and T_4, which were very close to room temperature.

In order to obtain the normalized mass flow $\rho u/(\rho u)_\infty$, measurements are made in the free stream and in the boundary layer. If the probe-entrance area A is assumed to be constant throughout the boundary layer the following expression is obtained. (For the validity of this assumption see below.)

$$\frac{\rho u}{(\rho u)_\infty} = \frac{\dot{p}_v \sum_n V_n/T_{vn}}{\dot{p}_{v_\infty} \sum_n V_n/T_{vn_\infty}} \tag{5}$$

The normalized mass flow is thus given by the ratio of the pressure derivatives multiplied by a function of temperature, correcting for different temperature distributions in the system at different positions in the boundary layer. The correction arises from the fact that the inlet of the system is heated to a temperature close to the stagnation temperature, which in turn varies through the boundary layer. The effect of raising the temperature in part of the system is the same as diminishing the volume of this part at constant temperature. The value of the correcting function is, however, close to unity and not very sensitive to errors in the assumed temperatures.

The advantages of this method of measurement, compared with measurement using a sonic orifice, are mainly that the complicated calibration of the sonic orifice is avoided and that the pressure in the system can be reduced considerably without affecting accuracy. The lower pressure level also reduces the risk of probe-entrance-shock detachment. It is therefore possible to make accurate measurements closer to the wall than was possible earlier.

The main sources of error in the new system are deviations from the assumed temperature distribution in the system and changes in the effective area of the probe inlet. In order to estimate

these effects the heat exchange in the heat exchanger has been calculated and the variation of effective area with different Mach and Reynolds numbers has been examined.

The main heat exchanger is shown in Fig. 7. The flow passes the exchanger in an annulus of which the inner surface is part of a solid brass rod and the outer surface is water cooled. The cooling water is pumped into the exchanger from a reservoir at constant temperature. It leaves the exchanger at a slightly higher temperature ($\Delta T \sim 5K$). The temperature on the surface of the rod is measured by thermocouples at two different points. These measurements showed that the temperature of the rod was fairly constant. The heat exchanger can therefore be approximated with a simple system as shown below.

Consider a section of length dx of the annular heat exchanger (Fig. 7). The effective area of the heat exchanger is then

$$dA_w = \pi(D + d)dx \tag{6}$$

and the cross sectional area of the exchanger

$$A = \frac{\pi}{4}(D^2 - d^2) \tag{7}$$

The extracted heat from the volume becomes

$$\alpha(T - T_w)dA_w = \alpha(T - T_w)\,\pi\,(D + d)dx \tag{8}$$

This must equal the heat loss in the volume which is

$$-\,dT\,c_p\,\rho u A = -\,dT\,c_p\,\dot{m} \tag{9}$$

Thus

$$\alpha(T - T_w)\,\pi\,(D + d)dx = -\,dT\,c_p\,\dot{m} \tag{10}$$

The solution of this equation is

$$\frac{T - T_w}{T_i - T_w} = \exp\left[-\frac{\pi(D + d)}{(D - d)}\frac{Nu\, k\, x}{\dot{m}\, c_p}\right] \qquad (11)$$

where the Nusselt number $Nu = \alpha l/k$ is based on $(D - d)$. T_i is the temperature at the entrance of the heat exchanger.

The Reynolds number for the flow in the heat exchanger, based on the hydraulic diameter $D_H = 4A/O$, is sufficiently low for the flow to be laminar. The Nusselt number is then 3.75 or higher, Ref. [8].

With the appropriate values of various constants, Eq. (11) now takes the form

$$\frac{T - T_w}{T_i - T_w} = \exp\left[-\frac{\pi(12+9)\ 3.75 \cdot 0.024\ x}{(12-9)\ 0.15\ 10^{-3} \cdot 10^{3}}\right] = e^{-13.195x} \qquad (12)$$

This means that the temperature difference between the flow and the wall is halved in ~ 5.3 cm. The resulting temperature profile is shown in Fig. 8. As seen, a length of 0.4 m should be sufficient to cool the flow at the present conditions.

In order to ensure that the heat produced in the flexible rubber tubing during the compression was removed, a second, smaller, heat exchanger was placed between the tubing and the measuring volume.

4.3 The AVA combined pressure-temperature probe

The AVA probe is shown in Fig. 9. A thermocouple is placed immediately behind the opening of a pitot tube. The diameter of the thermocoax is 0.5 mm and that of the thermothreads (Cromel-Alumel) is 0.1 mm. The ratio between the diameter and the length

of the thermothreads is made small in order to minimize heat losses by conduction. The conductors and the sheath are isolated from each other by Magnesia powder. A system of valves and sonic orifices allows the mass flow through the system to be varied. By closing the valves it is also possible to measure the pitot pressure. A more detailed description of the system is given in Ref. [9].

Meier, Ref. [9], has shown that the recovery factor of the thermocouple in a probe with suction is strongly dependent on the mass flow past the thermocouple. The dependence is shown in Fig. 10. It is seen that there exists a critical value of the mass flow below which the recovery factor starts to fall. Above this value r_p is approximately constant.

In the present tests the area of the suction controlling orifice was made large enough to keep the mass flow above the critical value in the entire portion of the boundary layer where measurements were made.

5. RECORDING OF DATA

The data were recorded on the Beckman 210 data acquisition system of the Hyp 500 facilities. The system accepts up to 50 low-level analog input signals, and records the input signals on magnetic tape in a digital format compatible with an ICL 1901-AS or IBM 360 computer. Thirty of the fifty low-level analog input channels are wired to signal conditioning units of the constant current type.

The low-level input cables between the wind tunnel and the system are carefully screened and enclosed in iron tubes to eliminate disturbances from electromagnetic noise fields. The system has eight sampling rates ranging from 1 Hz to 10 kHz. In the present tests the following variables were recorded:

p_o, T_o, p_v, T_1, T_2, T_3, T_4, T_s, and y

The sampling rate was 10 Hz.

6. DATA REDUCTION

The normalized mass flow is obtained from Eq. (5). With the present values of the subvolumes and the corresponding temperatures one obtains

$$\frac{\rho u}{(\rho u)_\infty} = \left(\frac{\dot{p}_v}{\dot{p}_{v_\infty}}\right) \frac{\left[\frac{18}{T_s} + \frac{25}{T_w + [\theta]_{ln}} + \frac{30}{T_3} + \frac{500}{T_4}\right]}{\left[\frac{18}{T_s} + \frac{25}{T_w + [\theta]_{ln}} + \frac{30}{T_3} + \frac{500}{T_4}\right]_\infty} \tag{13}$$

The pressure derivatives were obtained from the pressure recordings.

$$[\theta]_{ln} = \frac{\theta_1 - \theta_2}{\ln \frac{\theta_1}{\theta_2}}$$

is the logarithmic mean temperature difference of the heat exchanger. θ_1 equals the temperature difference between the flow and the wall at the entrance and θ_2 the difference between the flow and the wall at the exit of the heat exchanger.

In supersonic flow the following relations hold

$$\frac{p}{p_s} = \frac{\left(\frac{2\gamma}{\gamma+1} M^2 - \frac{\gamma-1}{\gamma+1}\right)^{\frac{1}{\gamma-1}}}{\left(\frac{\gamma+1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}}} = \frac{f(M)}{\gamma M^2} \tag{14}$$

$$\frac{\rho u^2}{2} = \frac{\gamma}{2} p M^2 \tag{15}$$

The static pressure is assumed to be constant across the boundary

layer. γ is assumed to be constant.

Thus $\rho u^2 = p_s \, f(M)$ (16)

where $$f(M) = \frac{1}{2.1328} \left(1.5 - \frac{0.2}{M^2}\right)^{2.5} \qquad (17)$$

for $\gamma = 1.4$.

Combining Eqs. (15) and (16) gives

$$M = \left[\frac{p_s \; f(M)}{p\gamma}\right]^{\frac{1}{2}} \qquad (18)$$

p is calculated from the stagnation conditions of the tunnel. M is then determined by an iterative process using Eqs. (17) and (18).

Knowing $\rho u/(\rho u)_\infty$ and $\rho u^2/(\rho u^2)_\infty$, u/u_∞ and ρ/ρ_∞ are easily obtained.

Again assuming constant static pressure across the boundary layer we have

$$\frac{T}{T_\infty} = \frac{\rho_\infty}{\rho} \qquad (19)$$

Now

$$\frac{T_s}{T_{s_\infty}} = \frac{T}{T_\infty} \, \frac{\left(1 + \frac{\gamma-1}{2} M^2\right)}{\left(1 + \frac{\gamma-1}{2} M_\infty^2\right)} \qquad (20)$$

and

$$\frac{T_s}{T_{s_\infty}} = \left[\frac{(\rho u)_\infty}{(\rho u)}\right]^2 \frac{p_s}{p_{s_\infty}} \, \frac{f(M)}{f(M)_\infty} \, \frac{\left(1 + \frac{\gamma-1}{2} M^2\right)}{\left(1 + \frac{\gamma-1}{2} M_\infty^2\right)} \qquad (21)$$

or

$$\frac{(\rho u)}{(\rho u)_\infty} = \left[\frac{T_{s_\infty}}{T_s} \cdot \frac{p_s}{p_{s_\infty}} \cdot \frac{f(M)}{f(M)_\infty} \, \frac{\left(1 + \frac{\gamma-1}{2} M^2\right)}{\left(1 + \frac{\gamma-1}{2} M_\infty^2\right)}\right]^{\frac{1}{2}} \qquad (22)$$

The recording from the AVA-probe was converted to temperature using a polynomial giving the conversion factor for Cromel-Alumel.

7. ACCURACY OF MEASUREMENT

7.1 The mass-flow system

The accuracy in the mass-flow measurements is mainly dependent on the following factors:

a) the accuracy of the pressure recording

b) the temperature distribution in the measuring system

c) the effective area of the supersonic intake of the probe

The different transducers are calibrated to give an error of less than 0.5 % in the region of interest. The temperature distribution is in principle accurately measurable. The approximations used will, however, give rise to an error. The correction for different temperature distributions in the system is, however, smaller than 1 %.

The intake area of the probe is assumed to be constant throughout the boundary layer. This assumption may be violated by detachment of the shock and by Reynolds number effects in the boundary layer.

A method of indicating whether the shock is attached or not has already been suggested, Ref. [3]. In order to investigate whether the probe is sensitive to changes in the Mach number and Reynolds numbers, the system has been tested in the FFA S5 wind tunnel at different Mach numbers. The probe was placed in the free stream where the mass flow could be calculated. The measured mass flow was then compared with the calculations. The results indicated that the effective area should be constant within 1 %. (See below.)

If the pertinent estimated errors in the measured quantities are allowed for and if it is assumed that there is an error of less than 1 % in the probe intake area then the total estimated error of the normalized mass flow is less than 2 %.

7.2 The AVA combined pressure-temperature probe

The error in the temperature measurements arises mainly from the conversion factor and the recovery factor. The recovery factor should be fairly constant if the mass flow through the probe is high enough, Ref. [9].

According to the manufacturer, the error in the thermovoltage and the conversion factor gives temperature measurements accurate to within 2.2 %, when measured in degrees centigrade. This gives an error of less than 1 % in the absolute temperature. The error in the recovery factor is assumed to be smaller than 1 %, giving a maximum total error of less than 2 %.

The error in the pitot-pressure measurement is smaller than 0.5 %. The Mach number depends only on pressure measurements and the error should therefore be less than 1 %. This leads to a maximum error of 2 % in the calculated mass flow.

8. RESULTS AND DISCUSSION

8.1 The probe-inlet area

In order to check the assumption of a constant probe-intake area, the mass-flow system was tested in the free stream of the FFA S5 facilities, Ref. [7]. Five different nozzles (M = 1.5, 2, 2.5, 3, 3.5) were used. The stagnation conditions were approximately equal to

$p_o \sim 100$ kPa

$T_o \sim 280$ K

$Re \sim 0.65 - 1.54 \cdot 10^7/m$.

The measured pressure derivative was divided by the calculated mass flow, which gives a parameter proportional to the probe-inlet area:

$$\dot{p}/\rho u \propto A$$

Three different probes were tested. The result is shown in Fig. 11. The size of a ± 1 % error is shown for each probe in the figure. As seen, the deviation at each Mach number is of this size or smaller except for probe 2. This probe was slightly damaged at the leading edge after the first two tests. The deviation before the damage was, however, low.

The effective area shows a slight tendency to decrease with increasing Mach number or decreasing Reynolds number. The change from M = 1.5 to M = 3 was of the order 1 % for probe 3 and 0.7 % for probe 1. It seems reasonable to assume that this change arises from changes in the flow close to the edge of the intake. With increasing diameter of the intake the relative size of the effective area change ought to decrease, which is also seen in the results from the experiments. The relative areas of the intakes from measurements of the diameters were 1:1.223:1.526. This compares well with the corresponding ratios obtained from the mass-flow measurements: 1:1.215:1.524 (at M = 2.5).

If A is not constant, then the method of normalizing the mass flow by the free stream value and assuming constant probe area will give rise to an error that increases towards the wall. If the errors in the effective area are due to Reynolds number effects they should, however, not be larger than those reported here, since the Reynolds number in the Hyp 500 tunnel is higher ($\sim 2.7 \cdot 10^7/m$).

8.2 *The heat exchanger*

The functioning of the heat exchanger was checked by the thermocouples mounted inside the system, see Fig. 4. A typical record of the temperature readings in the system during a run is shown in Fig. 12, where:

T_1 is the wall temperature of the solid rod at the entrance of the heat exchanger.

T_2 is the wall temperature of the rod in the middle of the exchanger.

T_3 is the temperature measured in a brass tube in the middle of the flexible tubing after the exchanger.

T_4, finally, is the temperature in the measuring volume.

As seen, all temperatures are affected by the opening and closing of the valve to the vacuum system. The thermocouples for $T_1 - T_3$, which are mounted inside the measuring chamber of the tunnel, show that this part of the system is heated during a run, whereas T_4 remains practically at the original mean temperature. When the valve is opened, hot air flows into the exchanger and the temperature at T_1 rises quickly. At the point where the thermocouples measuring T_2 and T_3 are placed these variations have almost disappeared. When the valve is closed the walls of the exchanger are cooled again. The variation of T_4 arises from the pressure changes in the measuring volume. The thermocouple is placed in front of the valve to the vacuum system. The temperature therefore falls rapidly when the valve is opened. When the valve is closed again the temperature returns to its initial value with an overshoot of approximately 1K due to compression of the gas. The differences in initial temperature are due to cold air flowing into the tunnel from the outside before the tests.

All in all, the temperature records show that the heat exchanger

works properly and that the temperature variations are kept within reasonable limits.

8.3 The mass-flow measurements

The mass flow in the boundary layer on the M4 nozzle wall of the FFA Hyp 500 wind tunnel has been measured using the new mass-flow system. The results of the measurements have been compared with the calculated mass flow obtained from measurements of stagnation temperature and stagnation pressure using the AVA combined pressure-temperature probe. The stagnation-temperature distribution is shown in Fig. 13. This temperature distribution was then used together with the stagnation pressure from each probe to determine the mass flow. Fig. 14 shows the normalized mass flow as a function of distance from the nozzle wall, obtained from direct measurements and the values calculated from the AVA-probe records.

The agreement is well within the limits of expected accuracy throughout the supersonic part of the boundary layer.

From the pressure records of the mass-flow probe it may also be concluded that the entrance shock is attached at all tested positions in the boundary layer.

9. CONCLUSIONS

The mass-flow distribution in the boundary layer on the M4-nozzle wall of the FFA Hyp 500 wind tunnel has been measured with a mass-flow probe. The results have been compared with the calculated mass flow obtained from simultaneous measurements of stagnation temperature and pressure, using a combined pressure-temperature probe. The agreement is within the limits of expected accuracy in the supersonic part of the boundary layer. It is therefore concluded that the system works well.

The advantages over the previous FFA probe are that (1) fewer parameters are involved in the data reduction and that (2) the pressure level in the system has been considerably reduced, thereby making the risk of entrance-shock detachment smaller. The system has proved reliable also in the low-stagnation-pressure region close to the wall.

Calculations of stagnation temperature from the mass-flow measurements are not very accurate because of the many parameters involved. The use of the mass-flow probe for temperature measurements cannot therefore be recommended if a high degree of accuracy is required.

It is felt that a combination of a mass-flow and a total-temperature probe would combine the best features of the FFA probe and the AVA probe. A later report will deal with such a probe.

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SYMBOLS

A	Area
a	Speed of sound
M	Mach number
T	Temperature
y	Distance from the wall
p	Pressure
u	Velocity
R	Gas constant
V	Volume
d	Diameter, inner
D	Diameter, outer
l	Length
O	Circumference
m	Mass flow
Nu	Nusselt number $\left(= \frac{\alpha l}{k}\right)$
$f(M)$	$\rho u^2/p_s$
k	Coefficient of heat conductivity
ρ	Density
γ	Ratio of specific heats
α	Heat-transfer coefficient
r_p	Recovery factor of a probe $\left(= \frac{T_{om} - T_\infty}{T_o - T_\infty}\right)$
$[\theta]_{ln}$	Logarithmic mean temperature

Indices

∞	Free-stream conditions
o	Stagnation conditions
om	Measured stagnation condition
s	Stagnation conditions behind a normal shock
v	Measuring volume
w	Wall
i	Initial

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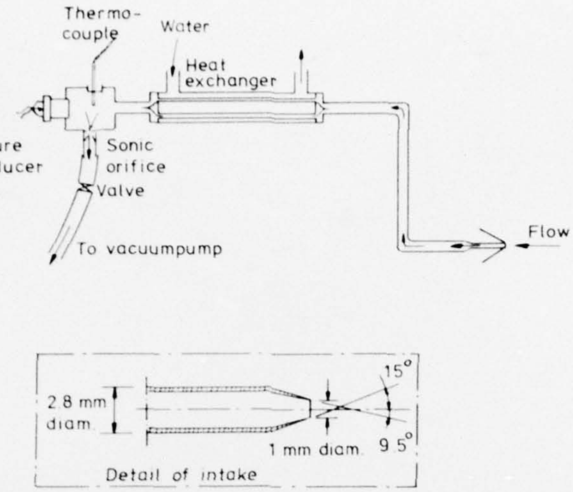

Fig. 1. The old FFA mass-flow measuring system - schematic arrangement.

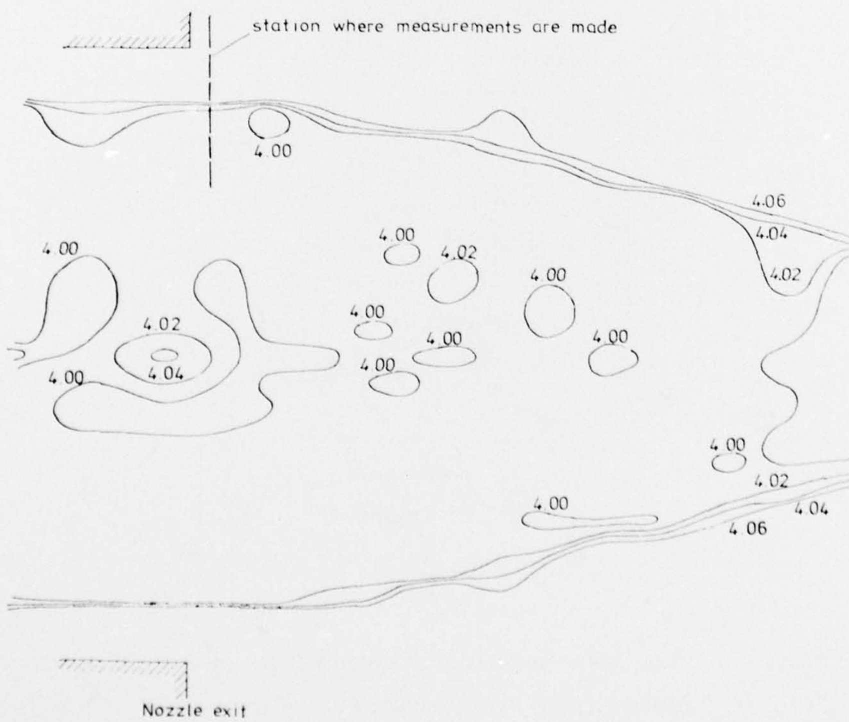

Fig. 2. Lines of constant Mach number $M_{nom} = 4$.

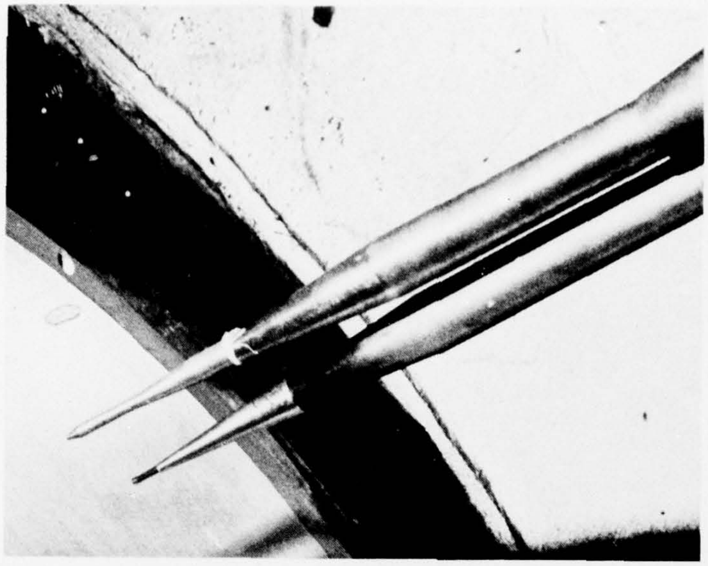

Fig. 3. The probes mounted in the windtunnel.

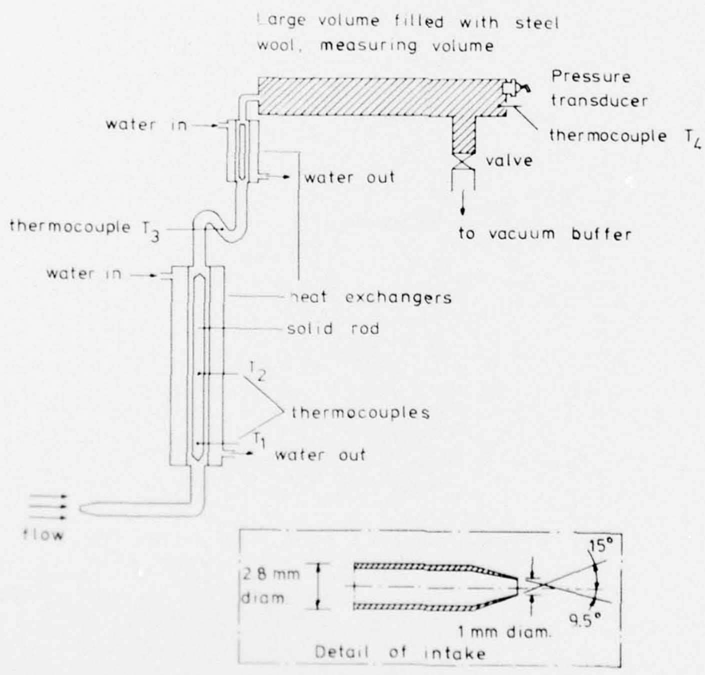

Fig. 4. The new mass-flow measuring system.
Schematic arrangement.

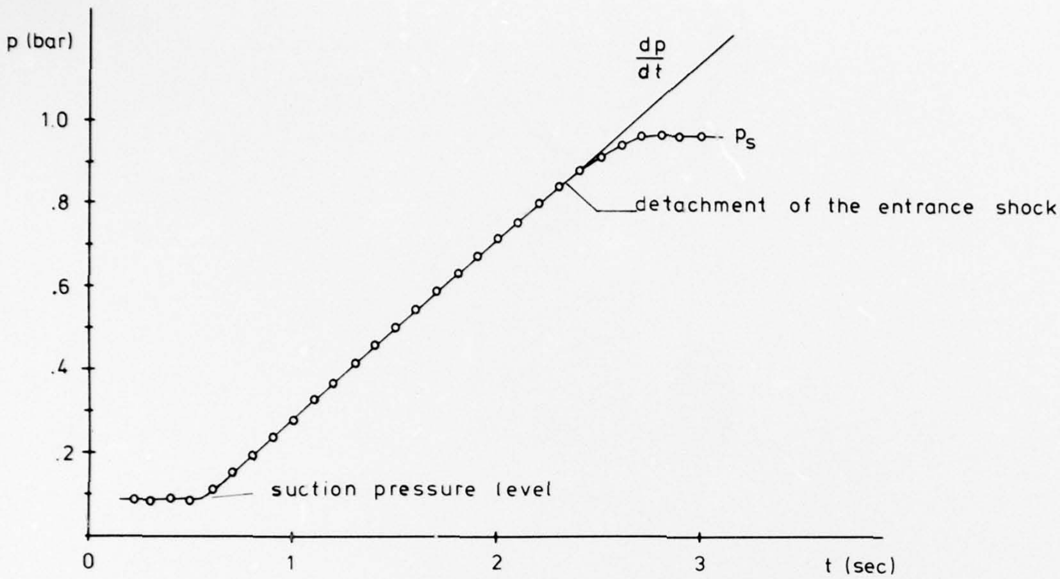

Fig. 5. Typical pressure record from the mass-flow system after closing the valve to the vacuum system.

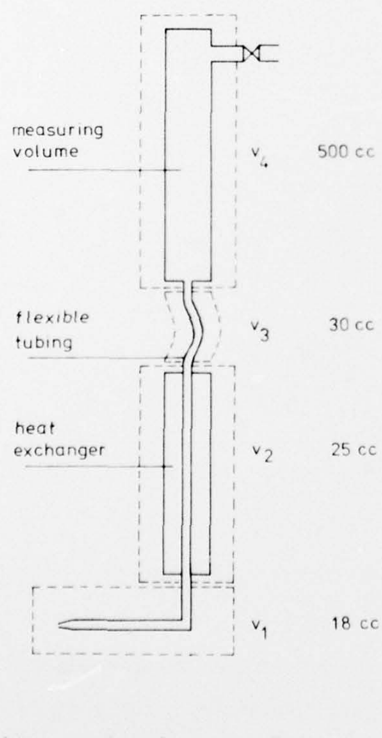

Fig. 6. The various subvolumes of the mass-flow system.

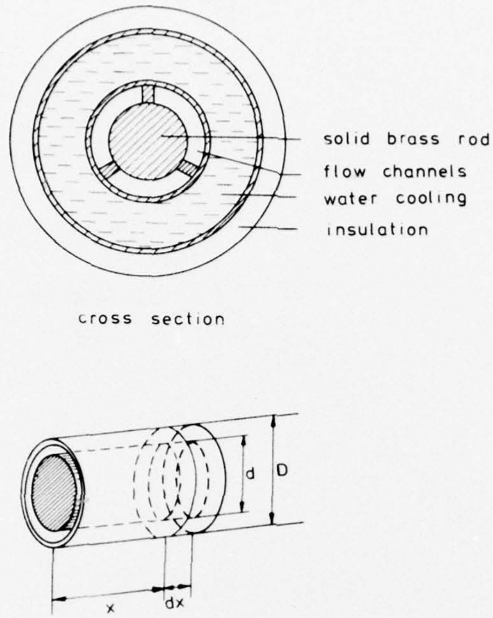

Fig. 7. Outline of the heat exchanger.

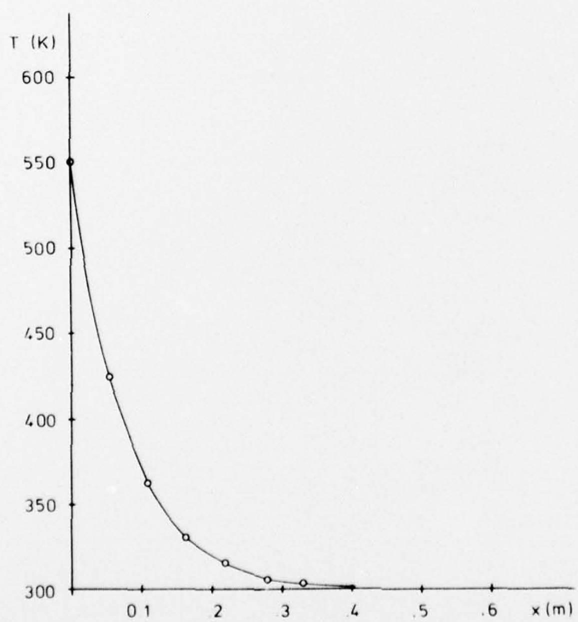

Fig. 8. Calculated temperature profile in the heat exchanger.

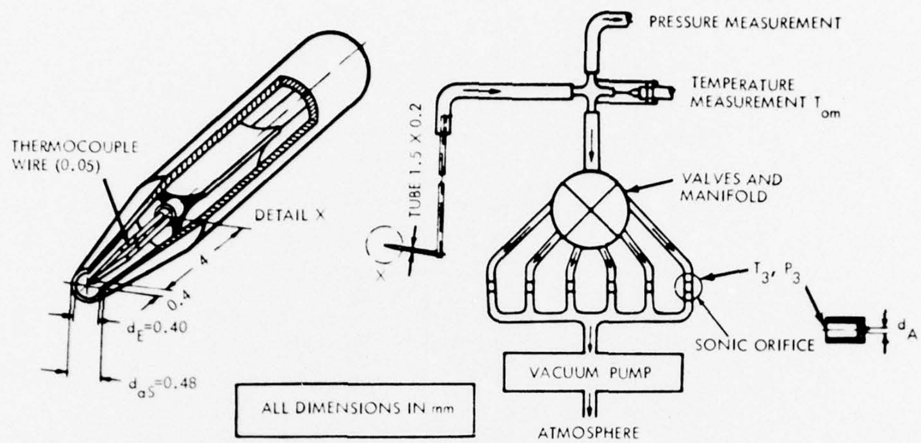

Fig. 9. The AVA combined pressure-temperature prove (from [9]).

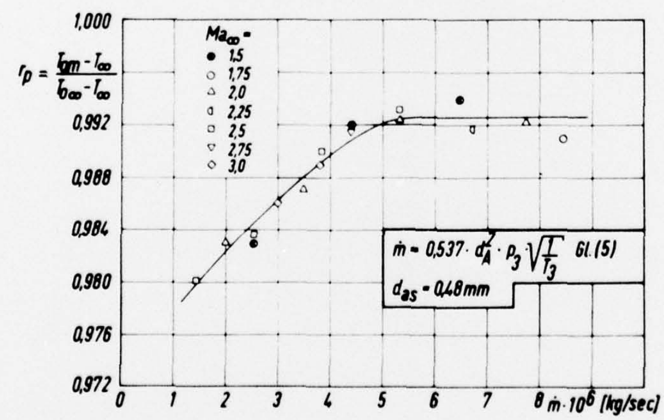

Fig. 10. The recovery factor vs mass-flow through the AVA combined pressure-temperature probe (from [9]).

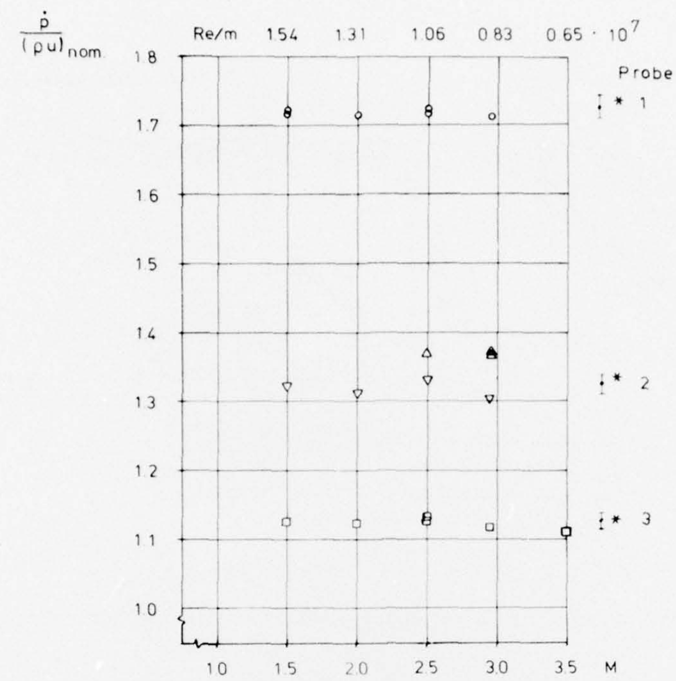

Fig. 11. Probe inlet area at different Mach numbers and Reynolds numbers. * ± 1%

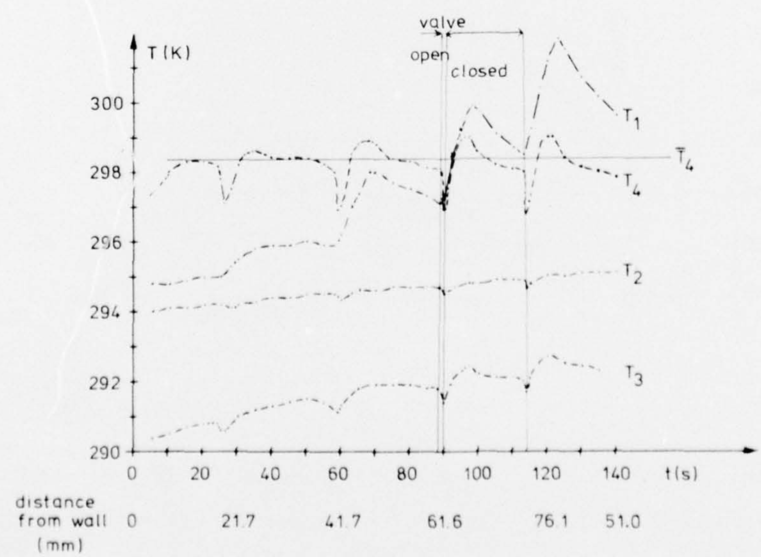

Fig. 12. Typical record of temperature measurements in the mass-flow system during a run.

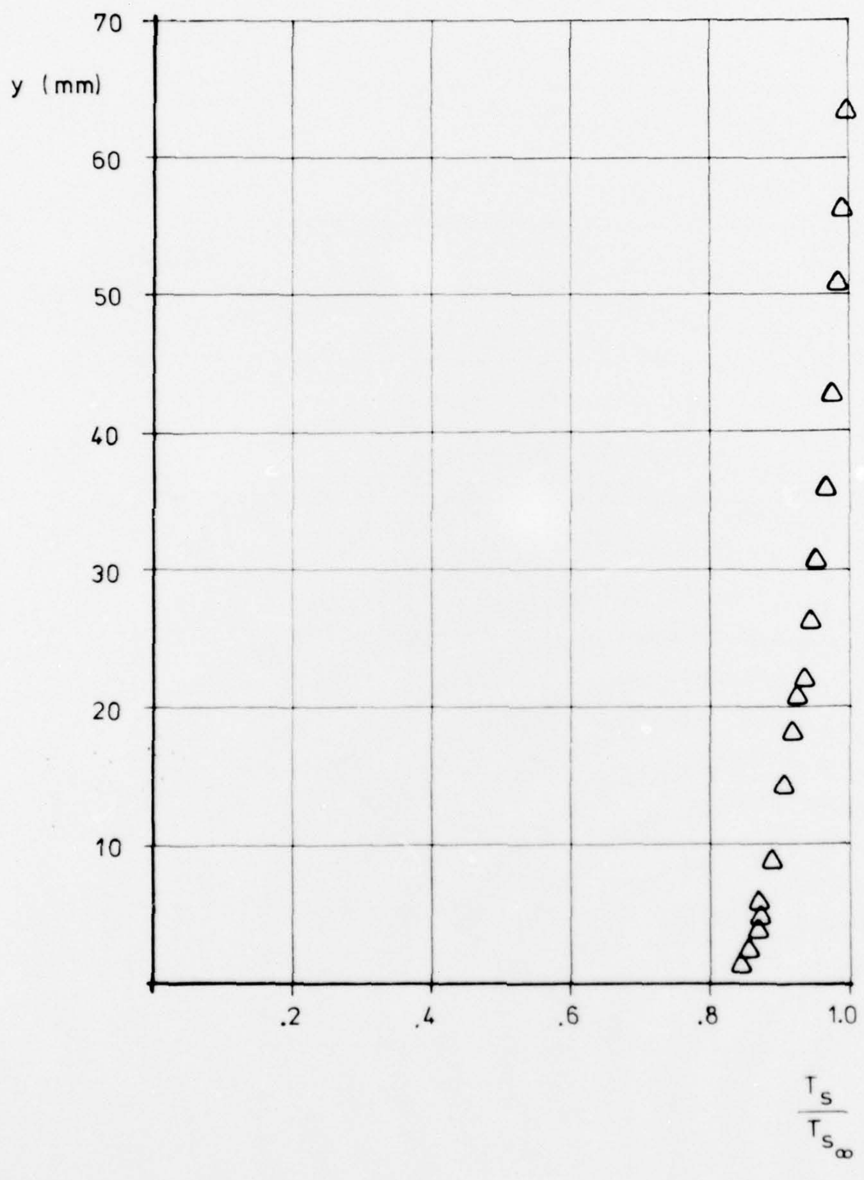

Fig. 13. The temperature profile in the boundary layer measured by the AVA probe.

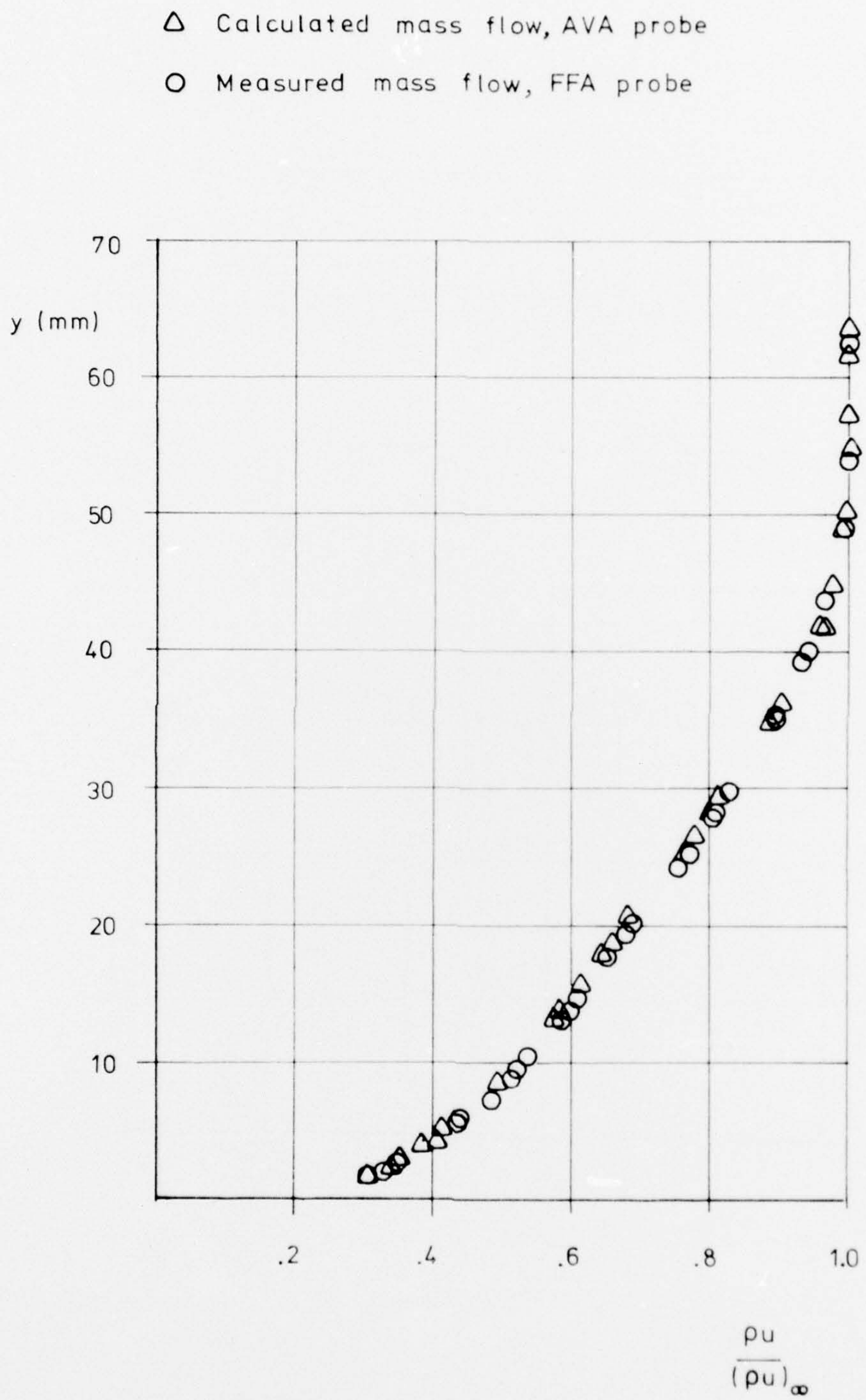

Fig. 14. The normalized mass flow in the boundary layer from measurements with the new mass-flow system and the AVA combined pressure-temperature probe.

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